RELATION OF YIELD AND PETIOLE SAP POTASSIUM LEVELS IN TOMATOES

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By

Stacy Ann Riede

Thesis Committee:

Robert R. Coltman, Chairman
Fred Rauch
Charles Murdoch

We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Horticulture.

THESIS COMMITTEE

Robert R. Coltman

Chairman

Charles L. Mundell

Fred D. Rauch

ABSTRACT

'Celebrity' tomatoes (Lycopersicon esculentum Mill.) were grown in peat-perlite under greenhouse conditions with five potassium (K) fertilization concentrations (25, 50, 100, 200 and 300 mg K/liter) in irrigation waters. Two experiments were conducted, one during the winter of 1989 (Expt. 1) and the other during the summer of 1990 (Expt. 2). In both experiments petiole sap K concentrations were monitored on a weekly basis with colorimetric paper test strips. Petiole sap K concentrations (mg K/ml) showed very little variation from plant to plant. However, petiole sap K concentrations varied considerably on a day-to-day basis.

The response of petiole sap K concentration to K concentration in the external solutions was quadratic in both experiments. Sap K levels in the summer trial (Expt. 2) were consistently higher than those in the winter trial (Expt. 1) at the same external concentrations.

Total and marketable fruit yield increased quadratically with increasing external K concentrations with a

plateau occurring at 200 mg K/liter (Expt. 1) and 190 mg K/liter (Expt. 2). The corresponding maximum marketable yields obtained were 2.7 kg/plant and 2.8 kg/plant, respectively.

The relationships between total and marketable yields and petiole sap K concentrations were quadratic in Expt. 2, with the maximum marketable yield occurring at 6.1 mg K/ml sap. The corresponding marketable yield was 2.8 kg/plant. Neither the linear nor the quadratic model fit well for yield vs. petiole sap K concentration in Expt. 1 data. However, the similarities of Expt. 1 to Expt. 2 data indicated that this relationship was best interpreted as quadratic. The maximum marketable yield was 2.7 g/plant in Expt. 1, with a corresponding sap K concentration of 5.7 mg K/ml sap.

Potassium petiole sap K concentrations between 5.7 to 6.1 mg K/liter appear to provide maximum marketable yield.

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Chapter 1

Introduction

Overview of fertilizer management problems.

As food production increases to meet the demands of a growing world population, so does the need for agricultural inputs such as fertilizers. High yielding varieties and subsequent cropping systems have made it necessary to replenish the soil with nutrients required for plant growth. The major nutrients for plant growth are nitrogen (N), phosphorus (P) and potassium (K). The efficient use of N, P and K fertilizers can dramatically increase crop yields.

Total world consumption of N, P and K fertilizers increased from 9 million metric tons in 1939 to 114 million metric tons in 1981 (FAO, 1983). Consumption of fertilizers is expected to increase in accordance with population and food demands. This is especially true in developing countries, where population growth in recent years has rapidly increased and more land is required for agricultural production to meet food consumption. The greatest potential for growth in agricultural acreage is in

the tropics on land now occupied by savanna and rain forests. The topography and climate in these areas favor agricultural production. However, soils in the tropical savannah and rain forests are usually highly weathered, acid infertile Oxisol-class and Ultisol-class soils having a low cation exchange capacity (CEC). These soils occupy more than 43% of the available land in the tropics (Sanchez and Salinas, 1981). They require high inputs of fertilizers to maintain maximum field production. Unfortunately, most developing countries do not have the transportation infrastructure to make these inputs readily available to the grower. Often, fertilizers are unavailable or expensive relative to the value of the crop. Competent and simple fertilizer management techniques are needed to efficiently use the available fertilizer.

In developed countries, fertilizers are readily accessible and inexpensive compared to the value of horticultural crops. As a result, growers tend to fertilize with nutrient levels in excess of the crops demands. This practice of "supra-optimal fertilization" insures that depletion of soil nutrients by heavy rains or soil micro-organism transformations will not exceed crops requirements. However, it is becoming apparent that this

practice has environmental consequences. Fertilizers that are not utilized by the plant are subject to becoming pollutants through leaching, soil erosion and gaseous losses. Nitrogen is readily leached from soils or can be lost in the form of nitrogen gas by micro-organism conversions. Phosphates can be lost by soil erosion or made unavailable to the plant by P-fixing soils. Potassium can also be lost by leaching or runoff and excess nutrients can contaminate ground-water sources. Soil erosion and run off also can increase the levels of nutrients in rivers and lakes. Excess nitrates and phosphates in suface water can cause an over-growth of algae and plants that can lead to the death or "eutrophication" of that water habitat. Excess nutrients in potable waters also can pose a health hazard to humans. Increasing public emphasis on environmental issues in recent years will lead to greater restrictions involving the future fertilizers.

Another possible ramification of over-fertilization is a decrease in yields by supra-optimal nutrient levels in the soil and plant tissue. In preliminary studies, excessive N fertilization caused decreased potato tuber, cucumber, pepper and tomato fruit yields (Marchner, 1986; Coltman, personal comm.). Excessive K concentration

decreased the starch concentration in potato tubers (Maschner, 1986). Excess fertilization of K may also lead to depressed uptake of Ca and Mg due to cation competition. Internal deficiencies of Ca cause physiological problems such as blossom end rot of tomato and tipburn of lettuce rendering the product unsalable (Trinklein, 1976). Excessive fertilization of K can also result in depressed B levels in celery tissue and an increase in the incidence of a 'brown checking' of the stem (Yamaguchi et al., 1958). It is very important to manage the amount of K applied to avoid such cation competitions and B uptake depression.

Environmental and production ramifications of supra-optimal fertilization practices in developed countries coupled with the high expense and low availability of fertilizers in developing countries justifies the need for an efficient system of fertilization based on a reliable measure of the crops's nutrient status.

Tissue analysis and fertilizer management.

Monitoring nutrient levels in plant tissue is a reliable method of insuring that the plant is recovers the available soil nutrients. The standard method of plant tissue analysis involves the use of expensive laboratory

equipment, skilled technicians and building facilities. In developed countries, private and some publicly funded laboratories will conduct tissue analysis for a fee. In developing countries, government-funded laboratories sometimes are available, but more commonly these services are non-existent. Another difficulty of conventional tissue testing, besides cost and availability, is the timeliness of reporting of the results to the grower. Because the analytical procedures are complex, it is common for weeks to transpire before analysis of a tissue sample can be completed and the results reported to the grower. Sometimes, the crop the analysis was performed on has been harvested and the analysis can only be used as an indicator for succeeding crops. Also the high cost of these kinds of analyses makes it uneconomical to continuously monitor the nutritional status of a crop throughout its development. These inherent difficulties of conventional laboratory tissue analysis may become less important in the future if grower-conducted analytical procedures based on rapid colorimetric paper test strips can be developed to reliably measure concentrations of specific nutritional elements in plant sap.

The use of rapid colorimetric paper analysis to measure concentrations of specific elements/molecules in

liquid is not a new concept. This methodology has been used for years in the medical field (e.g. blood glucose test for diabetics and pregnancy tests) on an over-the-counter basis for individuals to monitor their own health status. These tests are quick, inexpensive, simple and do not require the need for expensive equipment or trained personnel. Over the past decade, interest in rapid colorimetric nutrient analyses for NO_3-N content of vegetable and ornamental crops has increased. Like those tests used in the medical field, the current generation of proposed plant sap tests is simple and inexpensive, and seems to be sufficiently accurate for diagnosing crop nutrient status and developing fertilizer prescriptions in response to detected inadequacies.

Thesis problem and research objectives.

The high cost of greenhouse tomato production is acceptable because of the high net returns possible under good nutritional management. However, nutrient deficiences or supra-optimal levels of K can decrease marketable yields and profits by causing a number of severe physiological disorders of the fruit. Deficiencies of K can cause color disorders such as blotchy ripening, greenbacking or

greywall of the fruit (Forster, 1973; Picha and Hall, 1981; Trinklein, 1976). Excess K in the soil medium may result in cation competition with calcium (Ca). Tomato plants deficient in Ca have a higher incidence of blossom end rot disorders of the fruit (Forster, 1983). All of these fruit disorders mentioned make the fruit unsalable or decreases the value of the crop.

It would be valuable for a grower to periodically monitor and adjust both the N and K status of the crop to assure maximum marketable yields. However, currently available methods of nutrient analysis are expensive, time-consuming and require special equipment (Scaife and Bray, 1977). Colorimetric test paper strips for semi-quantative nitrate-nitrogen and potassium determinations now are available; these tests may be completed in less than 2 minutes. Previous studies investigating the suitability of rapid paper tests for monitoring nitrate nitrogen levels in vegetable crops showed promise for field usage (Prasad and Spiers, 1982; Coltman, 1985, 1987).

A preliminary investigation of the suitability of the K paper strip test as a rapid field method to monitor the nutrient status of a crop using greenhouse tomato (Lycopersicon esculentum 'Celebrity') will be reported in this paper.

The objectives of these studies were:

1. To evaluate the concentration of potassium (mg K/ml) in greenhouse tomato petiole sap over the crop cycle using rapid colorimetric paper tests, and develop appropriate sampling procedures for using petiole sap readings to diagnose crop K status.

2. To determine the relationship between petiole sap K concentration (mg/ml) and external K concentration (mg K/liter) using rapid colorimetric paper tests.

3. Determine the optimum external K concentration and petiole sap K concentrations associated with maximum marketable yields.

4. Determine the relationship between external potassium concentrations and the percentage of non-marketable yields.

Chapter 2.

Review of Literature.

The following narrative reviews previous research on rapid paper strip testing and, will proceed to give some background information on the importance of potassium on plant growth relevant to the tomato studies that follow. This information will be presented in sections as follows; I. Rapid semi-quantitative colorimetric quick paper test research, II. The role of potassium in plant development, III. Potassium uptake by plants, IV. Potassium and its availability in the soil or medium, V. Potassium fertilizer formulations, VI. Yield response to K fertilization and VII. Potassium deficiency and tomatoes.

I. RAPID SEMI-QUANTATIVE COLORIMETRIC QUICK PAPER TEST RESEARCH

Interest in simple nutrient field testing began in the 1940's with work done by Emmert (1942) and Nicholas (1948) on the NO_3-N status in plant sap. Unfortunately, this first generation of nutrient field tests was inaccurate and also required the use of dangerous reagents. In the 1970's

a new generation of easy-to-use, inexpensive and relatively accurate test strips were introduced into the market by Merck, Inc of Darmstadt, West Germany. These strips were named 'Merkoquant' test strips and were developed for monitoring NO_3-N in the environment, such as in rivers and lakes. The Merkoquant test is made of thin plastic strips, 75mm x 5 mm, with a square paper pad impregnated with the reagent N-(1-naphthyl) ethylenediamine attached at the tip. The reagent reduces nitrate to nitrous acid which produces a violet azo dye. The concentration of NO_3-N in the solution effects the intensity of the violet azo dye's color. The color intensity is compared to a scale provided to obtain the corresponding NO_3-N concentration. This test requires no reagents, equipment, or highly trained personnel.

The potential for this type of test to be used to rapidly determine a crop's nutrient status began to interest agricultural researchers. Evaluation of the utility of the rapid paper tests for plant sap NO_3-N analysis began in the mid 1970's with vegetable crops (Scaife and Bray, 1977). In New Zealand it was evaluated for use with ornamental crops (Prasad and Spiers, 1982), vegetable crops (Prasad and Spiers, 1984; 1985) and kiwifruit (Prasad and Ravenwood, 1986).

These authors concluded that sampling strategies must be considered to obtain accurate results using paper test strips. Sources of variation in petiole sap NO_3-N levels can come from several environmental or mechanical influences. Petiole NO_3-N content in the sap varies from plant-to-plant and by leaf position (Scaife and Stevens 1983; Tabor et al. 1984; Coltman, 1985). Diurnal swings in NO_3-N content in petiole sap is exhibited by beets (Minotti and Stankey, 1973). However, researchers found that other crops such as cabbage and tomatoes have petiole sap nitrate concentration which remains stable throughout the day (Scaife and Stevens, 1983; Coltman, 1987). Solar radiation levels and soil moisture content before or at the time of sampling may also have an effect on sap NO_3-N concentration. Work done on tomatoes found no correlation between solar radiation levels and sap NO_3-N concentrations (Coltman, 1987). Pruning the bottom leaves off tomatoes caused an unexpected increase in NO_3-N concentration in the sap that persisted for weeks (Coltman, 1987).

To reduce the impact of variation in petiole sap NO_3-N concentrations caused by environmental and mechanical factors, a number of sampling recommendations have been made. Sampling at the same time of day would simply solve

the problems of diurnal variation. Sampling from a large number of plants to account for plant-to-plant variation is recommended (Scaife and Stevens, 1983). Taking composite sap samples from many plants is also another method of reducing sample variation (Coltman, 1987). Routine (e.g. weekly) sampling provides information necessary to detect meaningful trends and to avoid misinterpretation of the significant day-to-day variation in NO_3-N levels commonly observed with NO_3-N in tomato petiole sap (Coltman, 1988). The use of an easily identified index tissue for sampling can reduce the sap NO_3-N variation due to leaf-position on the plant. Often plant sap is extracted from the petiole because of its ease of removal. Also, petioles contain high fractions of NO_3-N and K and are commonly used in standard tissue analysis. With tomatoes, the petiole of the youngest fully mature leaf usually third from the top is easily identified and used for both plant sap and tissue analysis (Reisenaur, 1976). Soil moisture fluctuations can be controlled with drip or sprinkler irrigation systems as is standard with many horticultural crops. To alleviate apprehensions about misinterpretation of rapid paper test results, an inexpensive hand-held reflectometer to electronically interpret the results of the NO_3-N paper

test is available commercially. This device was found simple to use and gave a precise interpretation of the results of the NO_3-N paper test for given standards (Jemison and Fox, 1988).

Nutrients in petiole sap are measured on a liquid volume basis (e.g. ug NO_3-N/ml of sap) using rapid tests whereas standard laboratory analysis and guidelines measure nutrients on a dry weight basis (e.g. %K, or mg NO_3-N/g of dry tissue). If it were possible to directly convert published guidelines to corresponding sap nutrient concentrations, the existing diagnostic information could be used to develop diagnostic sap nutrient guidelines. Unfortunately, the correlations between sap NO_3-N levels and petiole NO_3-N content on a dry weight basis have not been consistently found and it appears that calibration of sap NO_3-N levels to crop yields is necessary for the development of guidelines using these diagnostic values (Coltman, person. commun.). The relationship between petiole sap K concentrations and petiole K concentration on a dry weight basis has not been extensively studied. One study found a very high correlation between petiole sap K concentrations and K concentrations on a dry weight basis (Adams, 1982).

The amount of sampling necessary during a crop cycle is a major consideration for effective use of sap analysis. An attempt to use a single sample for quick nitrate sap analysis as a diagnostic tool to predict needed side-dressing to produce maximum yields in young brussel sprouts was unsuccessful (Scaife and Turner, 1987). Also Fox et al. (1989) had difficulty relating a single sampling of NO_3-N levels in corn stalks to grain yields. Coltman (1987) found that nitrate levels vary significantly from day-to-day on drip-fertigated greenhouse tomatoes. He recommended that a running average or trend analysis would be needed to accurately reflect the NO_3-N status of the crop. This could be accomplished by an active program using a regular sap testing schedule (e.g. weekly). The time-averaged values obtained could be immediately compared to the desired pattern of sap NO_3-N levels over the crop cycle. Adjustments in fertilizer application could be made immediately (Coltman, 1988), especially where fertilizer is applied through the irrigation.

This type of monitoring would be especially useful for a valuable horticultural crop whose nutrient status needs to be optimized throughout its cycle to guarantee maximum marketable yield. As more research is being done to

develop diagnostics and fertilization guidelines for the use of NO_3-N rapid paper tests, there becomes a need for similar research to be done for the other major plant nutrients. This would allow the farmer to monitor other crop nutrients simultaneously. Unfortunately, there is no similar method to monitor phosphorus in a solution, however rapid paper tests to monitor calcium (Ca) and K in a solution are now available. The K paper test fits the same physical description as the NO_3-N paper test, except that when the impregnated reagent in the filter paper pad contacts a solution containing K a red-orange dye is released. Unlike rapid paper test for NO_3-N, potassium paper test must be developed in a dilute solution of 0.1 M HNO_3 for one minute. The developing solution is usually provided with the test kit. The individual K paper test are inexpensive, costing $0.30 (U.S. dollar, 1990).

II. THE ROLE OF POTASSIUM ON PLANT DEVELOPMENT

Overview

Potassium is a highly mobile cation which travels and functions within plant cells, tissues and organs. It comprises more than one percent of the dry weight of

healthy vegetative plant tissues. The role of potassium is quite diverse, functioning as an osmotic regulator for cell extension, in stomatal movement, in leaf movements, and in phloem and xylem transport of solutes and synthates. It is also responsible for the activation of many enzymes of which some regulate protein and starch synthesis. Details of some of these functions will now be discussed.

Osmotic regulation and cell elongation

Cell elongation is dependent on two major factors; 1) an extendable cell wall, and 2) the accumulation of solutes in the vacuole to create an internal osmotic potential. Potassium and organic acid anions in the vacuole are the main solutes required for cell extension (Hashke and Luttege, 1975). Potassium affects the rate of cell extension by creating an electrically stable environment. As H^+ passes out of the cell, K^+ moves into the cell. This exchange of cations across the membrane maintains an electrically stable environment and allows the H^+ cations to loosen the cell wall making it more extendible and permeable. This process is known as the "Acid Growth Theory" (Rayle and Cleland, 1979). In Avena coleoptiles, indole-acetic acid (IAA)-induced-hydrogen-cation elongation

was inhibited by the absence of K^+ (Hascke and Luttge, 1975). The presence of K^+ enhanced the effect of cytokinins on cell elongation in cucumber cotyledons by four fold (Green and Muir, 1979). Effects of giberillic acids (GA), which also promote cell elongation in stems and roots (Mitchell et al., 1951), were enhanced by K^+ applications on sunflower plants (Guardia and Benlloch, 1980).

Osmoregulation and stomatal movement

Stomatal movement is regulated by turgor changes in the guard cells. These turgor changes are a result of the movement of K^+ in or out of the specialized cells. Potassium movement into a guard cell results in the uptake of water from adjacent cells. This increased turgor in the guard cells results in stomatal opening. Potassium movement out of the guard cell in turn closes the opening. Abscissic acid (ABA) produced by drought conditions promotes the efflux of K^+ from the guard cells, resulting in the closure of the stomatal opening (Mittelheuser and Van Steveninck, 1971).

Osmoregulation and leaf movement

Potassium plays an important role in the turgor regulated nyctinastic and seismonastic movements. Albizzia,

possesses nyctinastic movements where the leaves open during the day and close at night. The leaf movements are controlled by K^+ regulated turgor changes in the pulvini. This system is analogous to stomatal control where K^+ intake is driven by hydrogen pumping in the pulvini (Inglesias and Satter, 1983) and Cl^- acts as the major anion (Kumon and Tsurumi, 1984). In Mimosa pudica, mechanical stimuli will result in leaf closure for a period of time. This response is attributed to a redistribution of K^+ and therefore turgor pressure within the pulvini (Allen, 1969).

Phloem and Xylem Transport

Potassium is the most abundant inorganic element in the phloem, where it regulates the osmotic pressure and the movement of synthates from source to sink. Although the mechanisms are not yet known it is believed that K may also be an important component of active phloem loading (Marschner, 1986).

Enzyme Activation

Potassium is a univalent cation which is responsible for enzyme activation by causing a conformation change of the enzyme. Conformational changes of an enzyme by K^+ can increase the rate of catalytic reactions and in some cases

cause greater binding affinity of the substrate (Evans and Wildes, 1971). There are more than fifty (50) enzymes for which K^+ is a essential or promoting cofactor (Sueltor, 1970). High K^+ concentration is kept in the cytoplasm (100 to 120 mM) and in chloroplast (20 to 200 mM) to neutralize macromolecular anions and to maintain the pH between 7 and 8. This provides the optimum pH for most enzymes to function (Smith and Raven, 1979).

Potassium is needed by the regulatory enzymes responsible for starch synthesis. However, higher concentrations may inhibit starch synthesis (Preusser et al., 1981). Increased K^+ concentrations have been shown to decrease the starch content of potato tubers (Marschner, 1986).

Potassium also enhanced the ability of Mg^{+2} to activate plasma membrane bound adenosine triphosphatase (ATPase) in corn roots (Leonard and Hotchkiss, 1976). Activation of ATPase triggers the transport of external ion containing solutions across the membrane.

Protein synthesis

Potassium is used in the translation process of binding amino acids to create functional proteins. Potassium is believed to be involved in the binding of tRNA

to ribosomes (Evans and Wildes, 1971; Wyn Jones et al., 1979).

Deficiency of K^+ as a cofactor in protein synthesis impairs the production of Ribulose-bis-phosphate-carboxylase. A decrease in RUBISCO concentrations would adversely affect the plant's ability to fix CO_2. Also the accumulation of soluble nitrogen compounds such as amino acids, nitrates and amides in K^+ deficient plants reflects the need of K^+ as a cofactor in protein synthesis (Mengal and Helal, 1970).

Potassium and its role in photosynthesis

Potassium plays many roles in the efficiency of photosynthesis. As previously mentioned, K^+ plays a role in stomatal aperture which regulates the O_2:CO_2 gas exchange ratio and water loss. It functions as a cofactor to the synthesis of many enzymes, including RUBISCO which fixes CO_2 during photosynthesis. Potassium maintains a favorable pH in which photosynthetic reactions can occur. In the chloroplast K^+ is a dominant counter cation to light-induced H^+ movement across the thykaloid membrane. This movement creates a pH gradient across the membrane which drives ATP synthesis in photophosphorylation (Lauchili and Pflueger, 1978).

Also leakage of K^+ induced by antibiotics causes changes in the membrane integrity and function of chloroplast and proplastids. Plants with optimal K^+ concentrations in their tissue have increased rates of photosynthesis, photorespiration, and RUBISCO activity, and decreased dark respiration (Peoples and Koch, 1979). Plants which are K^+ deficient have higher respiration rates (Bottril et al., 1970)

III POTASSIUM UPTAKE IN PLANTS

In general, agricultural crops have uptake of potassium and nitrogen that are equal and twice as great as phosphorus. This gives the N-P-K uptake ratio of 2:1:2 which means that as much K is needed as N for optimum yield (Kaddar et al., 1984)

The rate of K uptake varies among species and even among cultivars of the same species. In general dicot crops have a higher K uptake rate than monocot crops. For example, tomatoes will have the same amount of K uptake in its 3 month crop cycle as sugarcane in its 12 month crop cycle (Nelson, 1968).

IV. POTASSIUM AND ITS AVAILABILITY IN THE SOIL OR MEDIUM

Soil type plays a vital role in the availability of potassium for plant uptake. In general, soils that have a low CEC will be unable to adsorb and exchange large quantities of K+. This is true for highly weathered Ultisol-class and Oxisol-class soils that comprise 43% of the land mass in the tropics (Salinas and Sanchez, 1981). Also soils that consist of high proportions of sand and organic matter have a low potassium content. In contrast soils with high proportions of clay are usually rich in K. Clay minerals such as alkali-feldspars and K-mica can contain up to 4-15% K by weight (Scheffer and Schachtaschabel, 1976). The main source of available K for plant growth is release by the weathering of these K containing clay minerals.

2:1 layer phyllosilicate clays can also fix K, making it unavailable to the plant. The extent to which K is fixed depends on the negative charge density and its location. The greater the negative charge the stronger K is fixed to the mineral. The position of the fixation and the wedge structure can also fix K by spatial matching. If

moisture content of a soil is low, water is lost from between the layers, which close, rendering K+, NH_4+, Rb+ and Cs+ trapped, while divalent cations are still available. NH_4^+ has a similar molecular radius to K+ and its presence may compete for fixation sites (Bartlett and Simpson, 1967).

V. POTASSIUM FERTILIZER FORMULATIONS

Potassium fertilizers are essentially salts of potassium in combination with chloride, nitrate, sulphate, polysulphate or magnesium sulphate. Most K fertilizers are water soluble. The most widely used potassium fertilizer is potassium chloride (KCl) which is also known as muriate of potash (Kaddar, 1984). Potassium chloride contains 50-53% K and is the most inexpensive source of K. However, when high rates of KCl are applied to acid soils higher concentrations of phytotoxic elements such as aluminum and manganese may be released into the soil solution (Tisdale, 1985). Also some crops such as potatoes and tobacco are highly sensitive to chloride and applications of KCl may decrease yields (Tisdale, 1985). Potassium chloride may also unfavorably increase chloride levels in crops

irrigated with water already containing high levels of chloride (Marschner, 1986).

Potassium sulfate (K_2SO_4) contains 42-44% K and 17% sulfur (S). The advantage of the use of K_2SO_4 fertilizers is that it supplies large amounts of K and S, which may be deficient in soils.

Potassium nitrate (KNO_3) contains 37% K and 13% N. The use of this fertilizers is restricted to high value crops by its expense. It is primarily marketed for use on vegetable crops and as a foliar spray for orchard crops. If KNO_3 production cost can be lowered, this fertilizer may rival other nitrogen fertilizers as a source for both N and K.

Potassium phosphates (KPO_3, $K_4P_2O_7$, KH_2PO_4, K_2HPO_4) have both high K and P analyses, however they are costly to produce. If technology were developed to inexpensively produce these types of fertilizers several important benefits in their use can be taken advantage. These benefits include a high P and K analysis, low salt index. Polyphosphates can be formulated having controlled solubility, free of chloride and flouride, thus making this fertilizer suited for use with Cl and F sensitive crops.

Potassium magnesium sulfate (K_2SO_4, $MgSO_4$) contains 18% K, 11% Mg and 22%S. This fertilizer is a double salt that benefits soils deficient in both S and Mg.

VI. YIELD RESPONSE TO K FERTILIZATION

When a soil is K deficient, fertilization with K can increase yields. Tomatoes grown on soil with 100 lbs exchangeable K/acre had a significant positive yield and quality response to 200 lb K/acre fertilization. There was a 60% yield increase along with a 156% increase in fruit quality (Wilcox, 1964). Significant yield increases due to potassium application have also been seen with a variety of vegetable, orchard fruit and grain crops (Kilmer et al., 1968). Potassium fertilizer applications of 600-900 t/ha on K fixing clay soils doubled the yield of both corn and wheat (Mengal and Kirkby, 1982). The yield response of a crop to K fertilization also depends on nitrogen nutrition. Optimal N fertilization, increases the yield response of K fertilization (Gartner, 1969; Heathcote, 1972). Likewise, applied N is only fully utilized if K supply is adequate.

Potassium can indirectly increase yields by raising the disease resistance of many crop species. Stalk rot and lodging are usually more severe in maize when K is deficient (Kruger, 1976). Potassium fertilization reduced the incidence of powdery mildew on wheat (Glynne, 1959) and fusarium wilt on bananas (Goss, 1968). There are many

crops for which K results in positive response to disease resistance. Although the mechanism is not completely understood, it may relate to the effect of K in promoting thicker outer epidermal walls which may provide a physical barrier to the entrance of disease organisms.

Potassium fertilization also increases tolerance to salinity and improves water use efficiency of crops by efficient regulation of the stomatal opening (Brag, 1972).

VII. POTASSIUM DEFICIENCY AND TOMATOES

Deficiency of K can cause discolorations of the fruit making it unsalable. These physiological fruit color disorders are named greenback (GB), blotchy ripening (BR) and graywall (GW). Greywall appears as grayish-brown discolorations seen through the outer fruit wall. Areas may become slightly depressed and roughened. Internally there is severe browning of the pericarp. Although the true cause of greywall is unclear it is believed to be an interaction between K and periods of wet cloudy weather. There are differences between cultivars in susceptibility to greywall and K applications have reduced the occurrence of GW in some cases (Picha and Hall, 1981). Blotchy

ripening appears externally as areas of yellow or orange discoloration intermixed with normal red areas. Blotchy ripening is associated with K deficiency (Picha and Hall, 1981). Greenback appears as a partial or complete ring of green or yellow tissue around the calyx end of the fruit. It associated with excessive sunlight and depressed K supplies (Forster, 1973).

Chapter 3

Materials and Methods.

Two experiments were conducted in a greenhouse at the Magoon Greenhouse Facility, Honolulu, Hawaii. In each experiment 105 tomato plants were grown from seed in 25-cm-diameter plastic pots containing 0.013 m^3 of 1 peat: 1 perlite (by volume) mixture amended with 1.7 kg dolomite/m^3, 4.2 kg gypsum/m^3 and 2.2 kg P/m^3 as triple superphosphate (0N-20P-0K). Micronutrients were incorporated as 1.5 kg Micromax/m^3 (Sierra Chemical Co., Milpitas, Calif.) and 2.8 kg MgSO4/m^3. Treatments consisted of five K levels (25, 50, 100, 200 and 300 mg K/liter) proportioned through five separate irrigation systems. Other nutrients applied through the irrigation were 200 mg NO_3-N/liter and between 125 and 250 mg Ca/liter, depending on K levels (Table 3.1). Treatments were designed to provide 200 mg NO_3-N/ liter and a minimum of 150 mg Ca/liter in external feed solutions. Supplemental applications of 0.13 kg Mg/m^3 formulated as $MgSO_4$, 0.3 kg P/m^3 formulated as triple superphosphate and

Table 3.1. The source and amounts of the major nutrients in each external feed concentration treatment for Expts. 1 and 2.

K concn. in external feed	N concn in external feed		Ca concn. in external feed	
KNO_3-K (mg/liter)	KNO_3-N (mg/liter)	$CaNO_3$-N (mg/liter)	$CaNO_3$-Ca (mg/liter)	$CaCl_2$-Ca (mg/liter)
25	9.3	190.7	234	0
50	18.6	181.4	222	0
100	37.3	163.7	199	0
200	74.5	125.5	154	0
300	111.8	88.2	108	42

K concn. in external feed	Chlorine concn. in external feed[y]
KNO_3-K (mg/liter)	$CaCl_2$-Cl (mg/liter)
25	0
50	0
100	0
200	0
300	75

[y]Municipal water contains 60 ppm Cl.
[z]Constraints: Each feed solution must contain 200 mg N/liter 150-234 mg Ca/liter.

1.04 kg Micromax/m^3 were made at 4 weeks after planting and every 4 weeks thereafter to the medium. Each pot received two 1-liter waterings daily from planting to 6 weeks after planting (anthesis) and two 2-liter waterings per day thereafter.

The experiments were arranged in a randomized complete block design with seven blocks and five treatments. Three plants per experimental unit (EU) were grown and harvested. If plant losses occurred due to Tomato Spotted Wilt Virus (TSWV) or other viruses, infected plants were rogued and data for the remaining plants in the EU were expressed on a per plant basis. Plants were arranged on 4.46 m^2 benches in two rows with 0.6 m of aisle space between benches. Each pot had 0.39 m^2 of of growing area.

'Celebrity' tomatoes were direct seeded, four seeds per pot on September 21, 1989 (Expt. 1) and March 26, 1990 (Expt. 2). The plants were thinned to two plants per pot at 3 weeks after planting. At 5 to 6 weeks after planting, sampling commenced on one of the two plants in each pot. The second plant was trellised and pruned to two leader stems per plant. At 8 weeks after planting, the untrellised plant was removed. This approach allowed one seedling to develop without being too seriously defoliated from sampling.

Plants were grown and harvested until thriftines and weekly fruit yields had noticeably declined, which insecticidal applications of Pydrin^{tm} (Expt. 1) and Pounce^{tm} (Expt. 2) were sprayed at recommended rates to control whiteflies. Poor insecticidal efficacy (Expt. 1) and equipment failures (Expt. 2), led to poor control of the whitefly and leaf miner infestations. Recommended applications of the fungicide Ridomil^{tm} prevented the occurrence of late blight. The trials was 21 weeks for (Expt. 1) and 18 weeks for (Expt. 2). Data on plant height, number of flowers at and beyond anthesis and number of flower trusses were taken at anthesis (7-8 weeks after planting).

Potassium levels in irrigation waters were monitored on a weekly basis with a flame photometer (Corning Model 410C) per instructions (Cole-Parmer Instrument Co., 1987) and adjusted as needed. Conductivity of pot-leachate solutions were measured at 15 weeks after planting (WAP) (Expt. 1) and 16 WAP (Expt. 2) using a hand-held meter. Conductivity of solutions was found to be between 1.4 to 2.7 dS/m. Environmental data was monitored using a LI-COR Model LI-1000 datalogger equipped with a shaded thermocouple for air temperature measurements and a quantum

sensor for light measurements. Minimum, maximum and average air temperatures and light levels were recorded daily from data collected at 5 minute sampling intervals. Averages of weekly minimum and maximum air temperatures are presented in Figure 3.1. Average weekly photosynthetically active radiation and photosynthetic photon flux are shown in Figures 3.2 and 3.3, respectively.

Sampling and Sap testing

Petiole tissue sampling commenced at 6 weeks after planting and was conducted every 7 to 10 days thereafter. Leaves were excised for analysis from one of the two leader stems of the plant on alternating weeks. The youngest fully unfurled leaf, usually third from the top was used for the analysis. The petiole was removed up to the first leaflet and the sap was expressed using a garlic press. The sap was diluted 10-fold (100 ul sap:900 ul water) using a micro-pipette. EM-Quant potassium test strips (EM Quant, E.M. Science, Gibbstown, N.J.) and Quantofix potassium test strips (Macherey-Nagel, GmbH & co., D-6160 Duren, West Germany) were used to monitor sap concentrations. Potassium concentration determinations with both brands of test strips were made visually by comparing strips to a

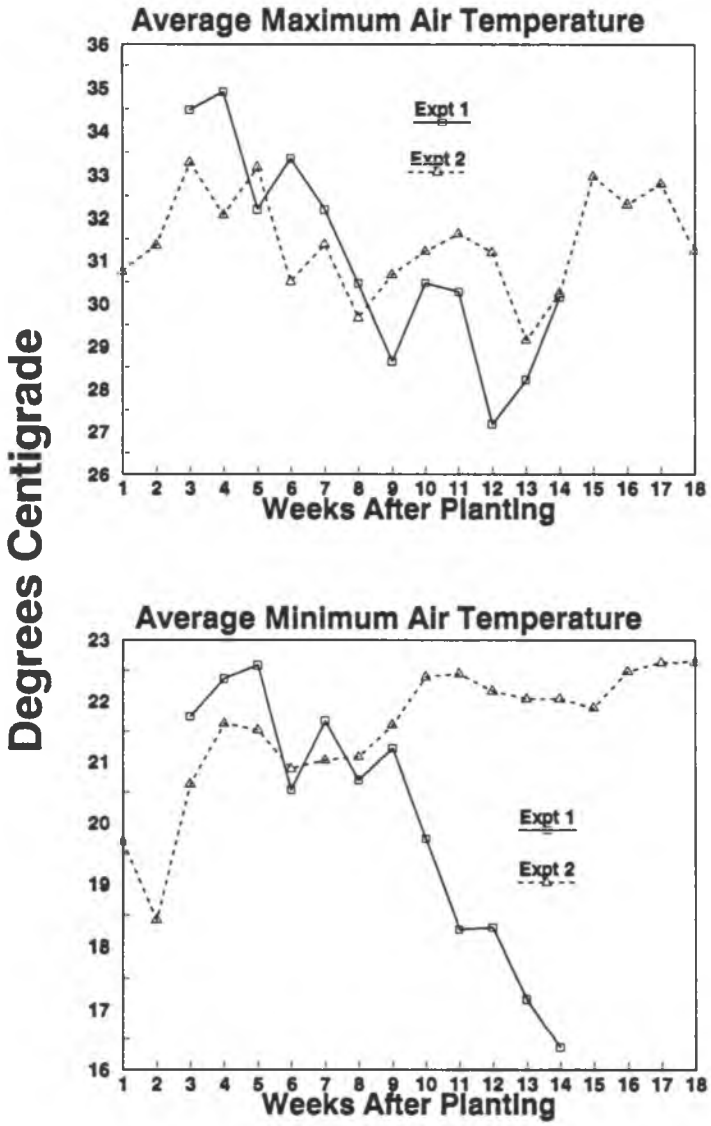

Figure 3.1. Averaged minimum and maximum weekly air temperatures (^{o}C) for both experiments.

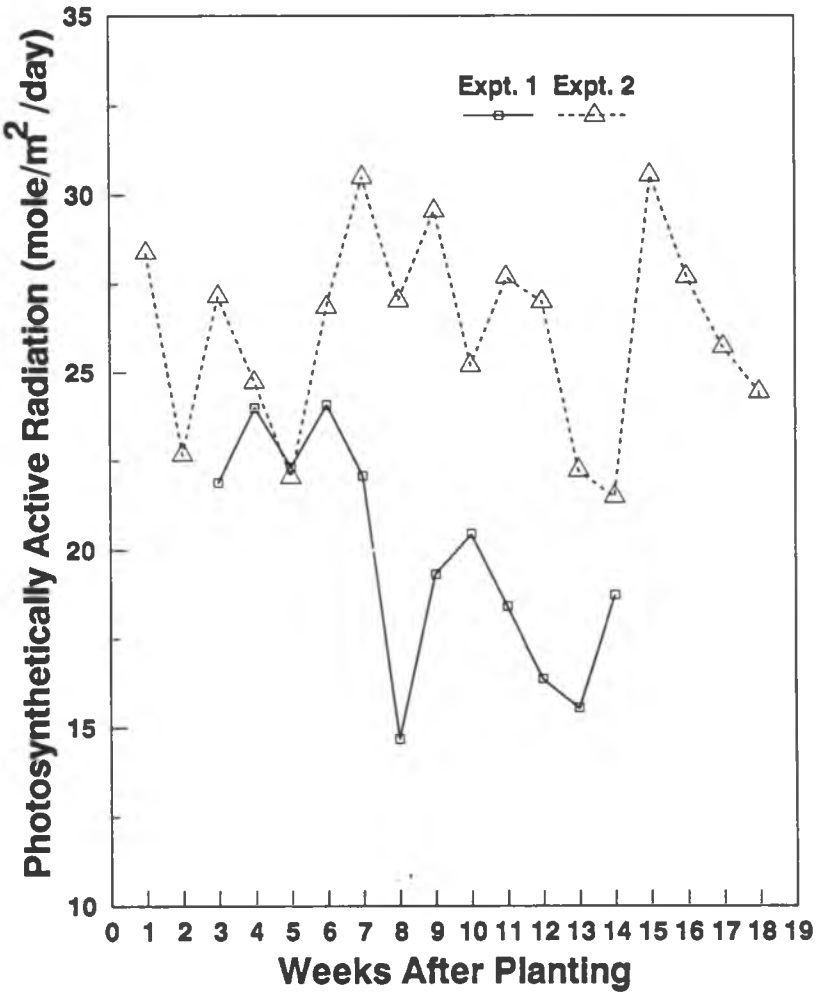

Figure 3.2. Averaged weekly photosynthetically active radiation for both experiments.

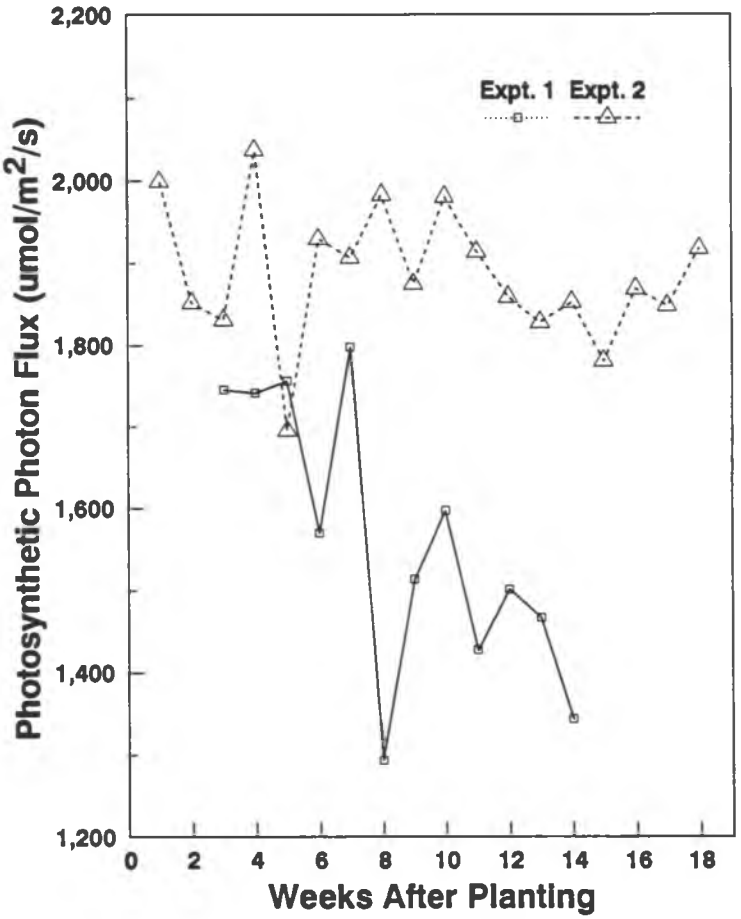

Figure 3.3. Weekly averages of maximum daily photosynthetic photon flux rates for both experiments.

color scale which was provided. Both brands of potassium paper test strips were found to be comparably accurate, athough the Quantofix strips are somewhat easier to use. Quantofix strips were used exclusively about a third of the way into Expt. 1 and throught out Expt. 2 because EM-Quant strips became unavailable from the manufacturer.

Recently matured whole leaves were sampled for tissue analysis at anthesis in both experiments. Tissue samples were analyzed by inductively coupled plasma spectrometry for tissue concentrations of P, K, Ca, Mg and B at the University of Hawaii Agricultural Diagnostic Service Center (UH-ADSC). Total N was analyzed by the UH-ADSC using semi-automated micro-Kjehldahl procedure modified to recover nitrates (Coltman, 1988). Tissue analysis results confirmed adequate status of nutrients other than K in both experiments (Table 3.2 and 3.3).

Harvest Procedures

Fruits were harvested at or beyond the breaker stage and each fruit was individually labeled with its plant identification code using a marker pen. Data were collected on individual fruit weight and grade. Unmarketable fruit was classified as small size, blossom

Table 3.2. Nutrient composition of whole-leaf samples from 'Celebrity' tomato plants at anthesis for Expt. 1.

K concn. in irrigation (mg/liter)	Leaf nutrient concentration (dry wt basis) N%	P%	K%	Ca%	Mg%
25	5.86	0.5	3.10	2.73	0.42
50	5.39	0.49	3.93	3.14	0.54
100	5.49	0.45	5.71	2.83	0.44
200	5.36	0.41	5.99	2.71	0.54
300	5.48	0.43	6.18	2.21	0.44

Table 3.3. Nutrient composition of whole-leaf samples from 'Celebrity' tomato plants at anthesis for Expt. 2.

K concn. in irrigation (mg/liter)	Leaf nutrient concentration (dry wt basis) N%	P%	K%	Ca%	Mg%
25	5.55	0.53	3.09	2.79	0.45
50	5.63	0.54	3.92	2.72	0.47
100	5.83	0.44	5.16	2.36	0.36
200	5.61	0.46	5.46	2.13	0.42
300	5.72	0.47	5.61	1.94	0.4

end rot, misshapen, scarring, cracking, splits, cat face and unusual scarring. Unusual scarring was a unique phenomenon which only occurred in Expt. 1. This defect is best described as numerous concentric scars on the calyx end of the fruit.

A modified version of the Hawaii Department of Agriculture Standards for Hawaiian Grown Tomatoes (1974) served as a guideline for determining marketability. The guideline was modified to allow the inclusion of tomatoes with color disorders in marketable yield totals. This was done because TSWV (Expt. 2) and whiteflies (Expt. 1 and 2) caused color disorders that would not have occurred in the abscence of these problems (Cantliffe, 1989 and Cho et al. 1989).

Best-fit curves for relationships between fruit yields (kg/plant), potassium petiole sap concentrations (mg K/ml) and potassium concentrations in the external feed solutions (mg/liter) were calculated using polynomial models. Only coefficients significant at $P<=0.05$ were retained in the models.

Chapter 4.

Results and Discussion

Potassium levels in petiole sap remained stable throughout the crop cycle at each feed concentration in Expt. 1 (Figure 4.1). Linear regression analysis confirmed the lack of significant trends ($P < 0.05$). Therefore the values averaged over time are used to represent the K concentration in petiole sap at each external feed concentrations in subsequent analyses. In Expt. 2, all K levels in the petiole sap were stable throughout the crop cycle, except at the 50 mg K/liter external feed concentration, where there was a significant positive linear trend (Fig 4.2). This trend was considered an anomaly, and the average value over the crop cycle was used in subsequent analyses as at the other levels.

Nitrate-N concentrations in petiole sap varied significantly from plant to plant (Coltman, 1987). In contrast, the variation in sap K levels from plant to plant was relatively low. Because of this low variation in petiole sap K levels, fewer plants would need to be sampled to achieve the same level of confidence about mean crop K

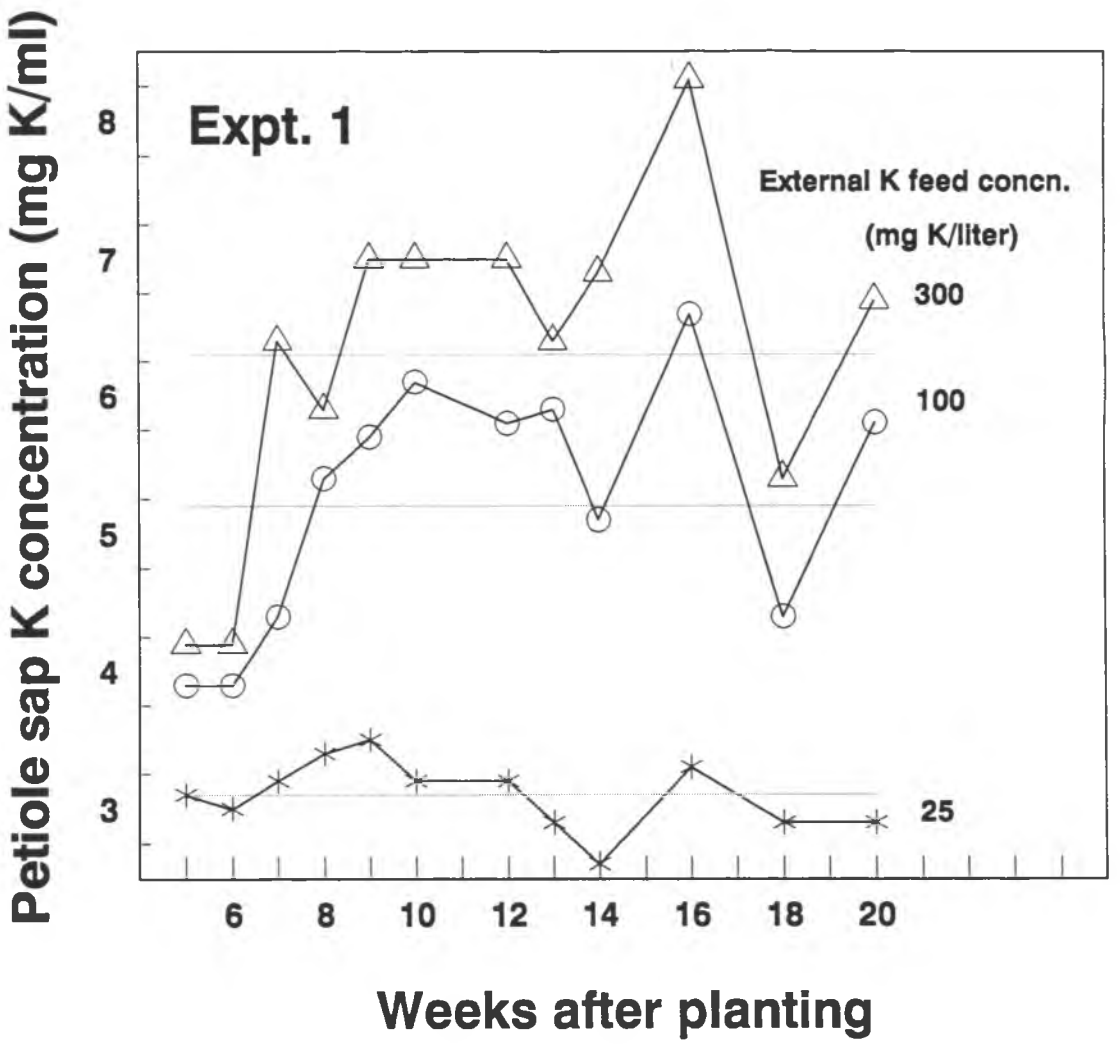

Figure 4.1. Response of petiole sap K concentration (ug/ml) over the crop cycle in Expt. 1. Three of the five external feed concentrations are represented. Averaged C.V. for plant-to-plant variation is 11.2 percent.

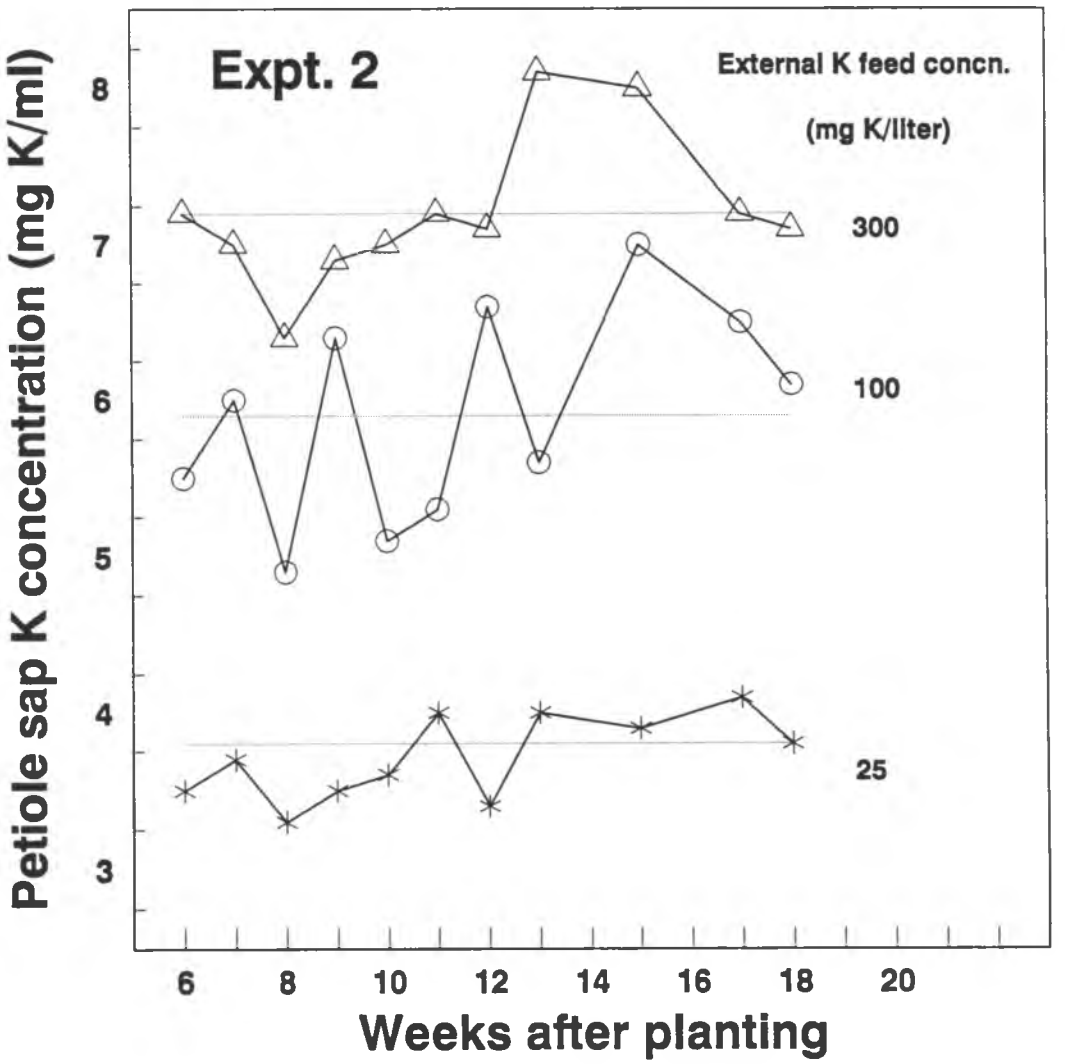

Figure 4.2. Response of petiole sap K concentration (ug/ml) over the crop cycle in Expt. 2. Three of the five external feed concentrations are represented. Averaged C.V. for plant-to-plant variation is 9 percent.

status than are required for NO_3-N. Day-to-day variation in NO_3-N levels in petiole sap is significant (Coltman, 1987). Likewise, potassium in petiole sap also seems to vary considerably on a day-to-day basis. As in the case of NO_3-N, weekly samplings probably are adequate to monitor the crops nutrient status. As with petiole sap NO_3-N, variable petiole sap K levels can probably be quantified adequately using an average of weekly sampling data over the cycle.

Potassium concentrations in petiole sap as determined by rapid paper tests were quadratically related to external feed concentrations (Fig. 4.3). Sap concentrations in Expt. 2 were consistently higher than in Expt. 1 at the same levels of K in the irrigation system. The reasons for this are unknown. Since light levels were higher in Expt. 2 than in Expt. 1 (Fig. 3.2 and 3.3), it is possible that K uptake was greater in Expt. 2 due to the availability of more energy from enhanced photophosphorylation. Potassium uptake by plant roots is known to be energy-requiring (Cheeseman and Hanson, 1979).

Total (marketable + cull) and marketable yields responded quadratically to increasing K concentrations in irrigation waters in Expt. 1 (Fig 4.4) and Expt. 2 (Fig.

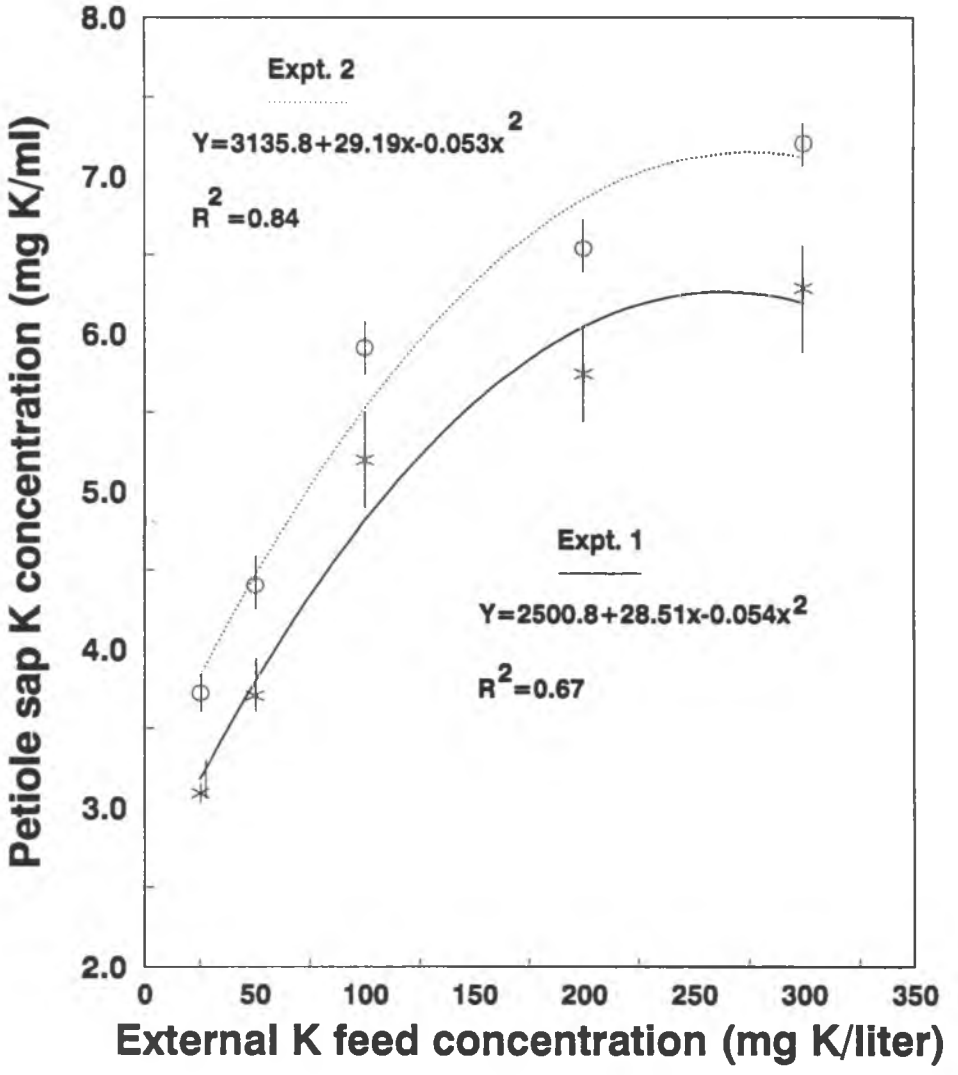

Figure 4.3. Correlation between petiole sap K concentration (ug/ml) and external K feed concentration (mg/liter) in Expt. 1 and Expt. 2. Vertical bars represent the standard error of the mean.

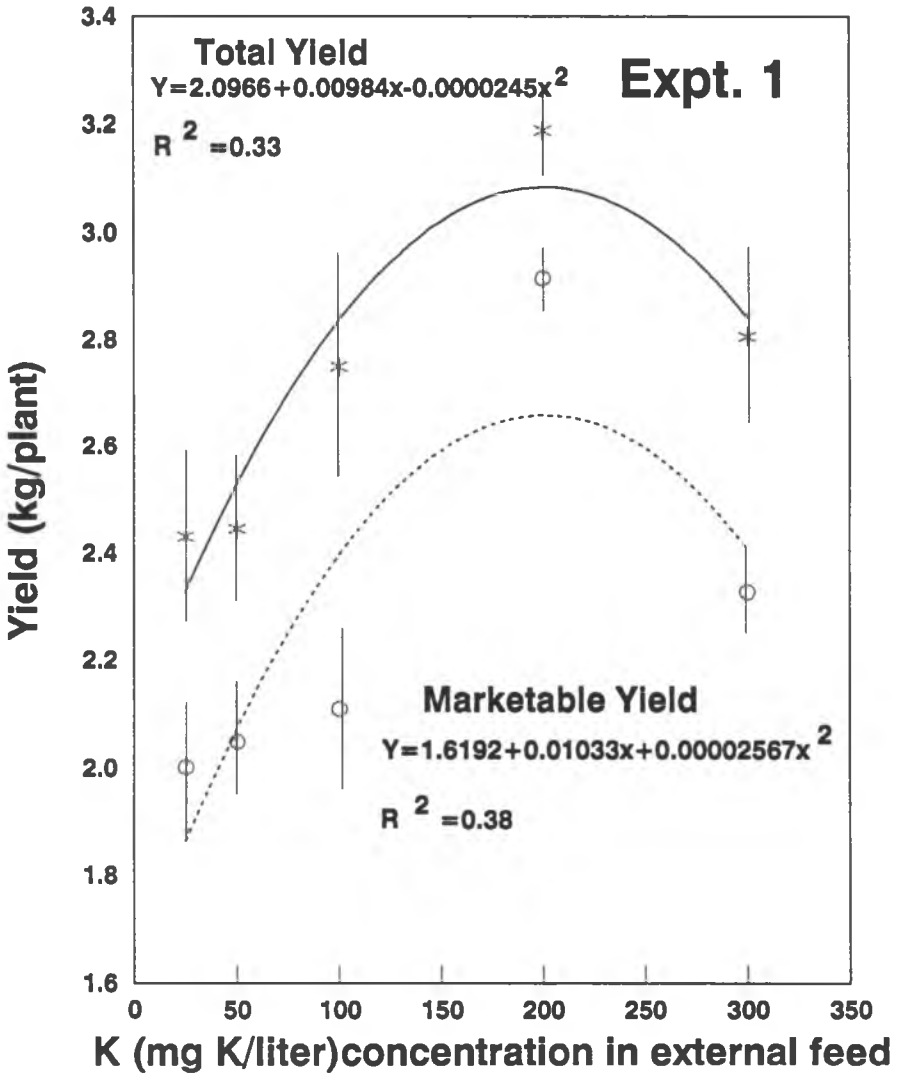

Figure 4.4. Correlation between total and marketable yield (g/plant) and external K feed concentration in Expt 1. Vertical bars represent the standard error of the mean.

4.5). The optimum K external feed concentration for greatest marketable yield was 200 mg K/liter (Expt. 1) and 190 mg K/liter (Expt. 2), with corresponding marketable yields of 2.7 kg/plant and 2.8 kg/plant, respectively. The marketable yields obtained in previous studies using the same cultivar and similar cultural conditions were 3.5 kg/plant (Coltman, 1987). The lower marketable yields in these experiments may be accounted for by high infestations of whiteflies and serpentine leafminers during the harvest period. Also, cloudy and rainy days in Expt. 1 coupled with large amounts of honey dew produced by a heavy whitefly infestation promoted the extensive development of sooty mold which covered tomato leaves and fruit.

The 300 mg K/liter treatment total yield (kg/plant) was 10 to 12 percent less than the 200 mg K/liter treatment for both experiments. Although there was 75 mg/liter more chloride in the 300 mg K/liter treatment, it is doubtful that toxic chloride levels are responsible for the observed declines in yields in both experiments. Chloride sensitive plants show injury between 70-140 mg Cl/liter. The threshold for chloride injury to tomatoes range from 140 to 350 mg Cl/liter (Shaw et al., 1975). The 300 mg K/liter external feed solution had a total Cl^- concentration of 135

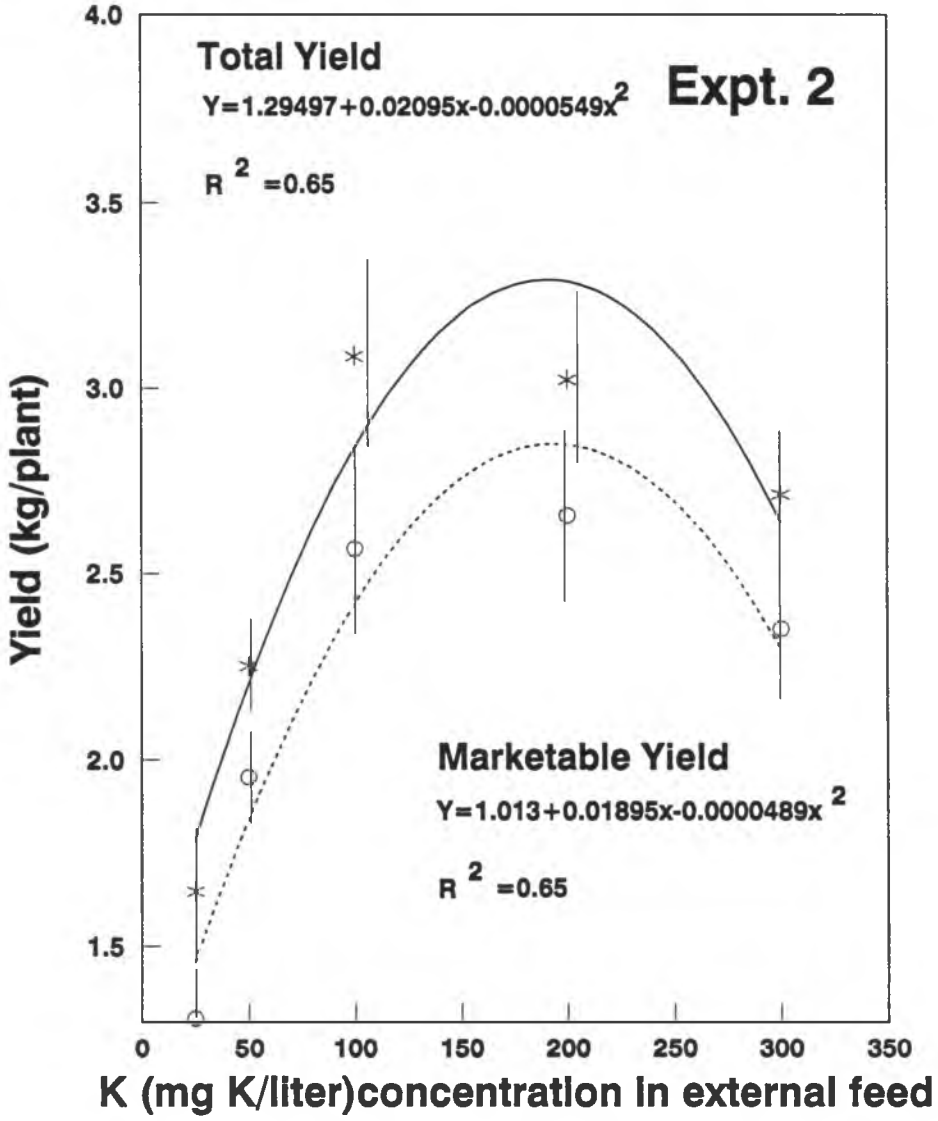

Figure 4.5. Correlation between total and marketable yield (g/plant) and external K feed concentration in Expt. 2. Vertical bars represent the standard error of the mean.

ppm. Therefore, it is more likely that excessive K rather than Cl toxicity is the primary cause for the significant reduction of yields.

The relationships between total and marketable yields and internal petiole sap K concentrations were quadratic in Expt. 2 (Fig 4.7), with the maximum marketable yield occurring at 6.1 mg K/ml sap. The corresponding marketable yield was 2.8 kg/plant. Neither the linear or the quadratic model fit well for yield vs. K concentration in petiole sap in Expt. 1 data, (Fig. 4.6) but the clearly quadratic relationship in Expt. 2 and the yield reductions found at the highest K feed level in Expt. 1 strongly suggest that the relationship between petiole sap K and yield in Expt. 1 is best interpreted as quadratic, with an optimum sap concentration (5.7 mg K/ml) occuring at the treatment mean of the 200 mg K/liter treatment.

At anthesis, plant height increased with increasing external K feed concentrations in Expt. 1 (Table 4.1) and Expt.2 (Table 4.2). Stem caliper (diameter), only measured in Expt. 2, also was found to be greater at higher external K feed concentrations (Table 4.2). Together these data support a strong influence of fertilizer K on plant vigor during the vegetative phase. The number of flowers at or

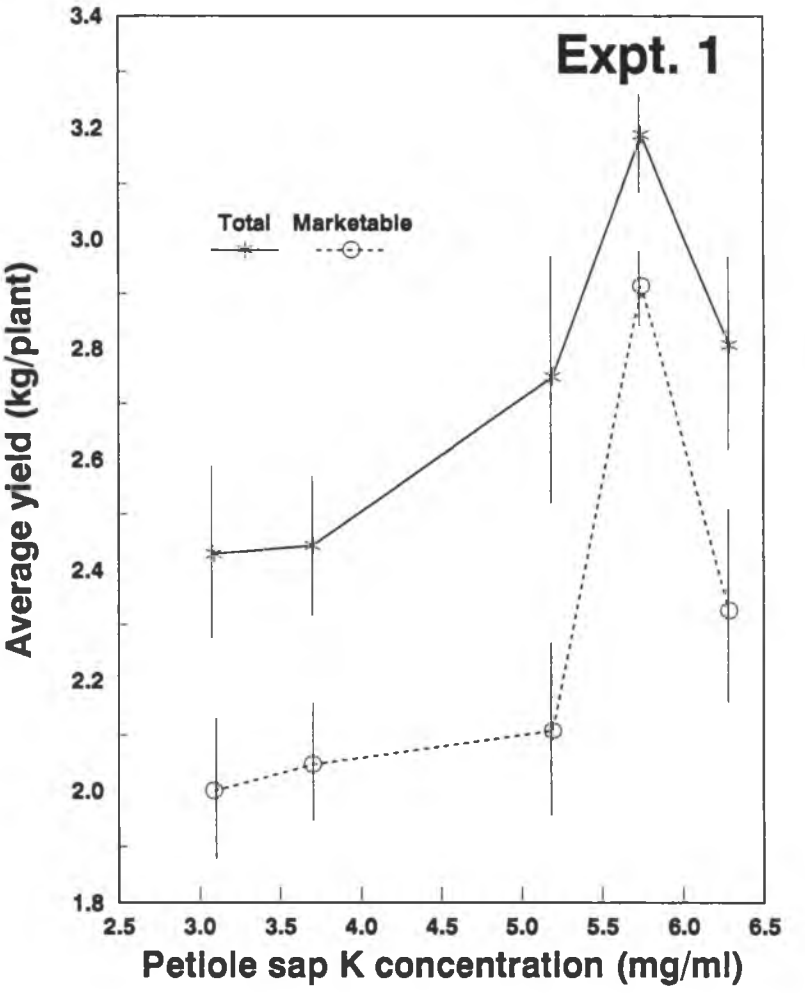

Figure 4.6. Representation of total and marketable yield (g/plant) vs. petiole sap K (ug/ml) concentration in Expt 1. Vertical bars represent the standard error of the mean.

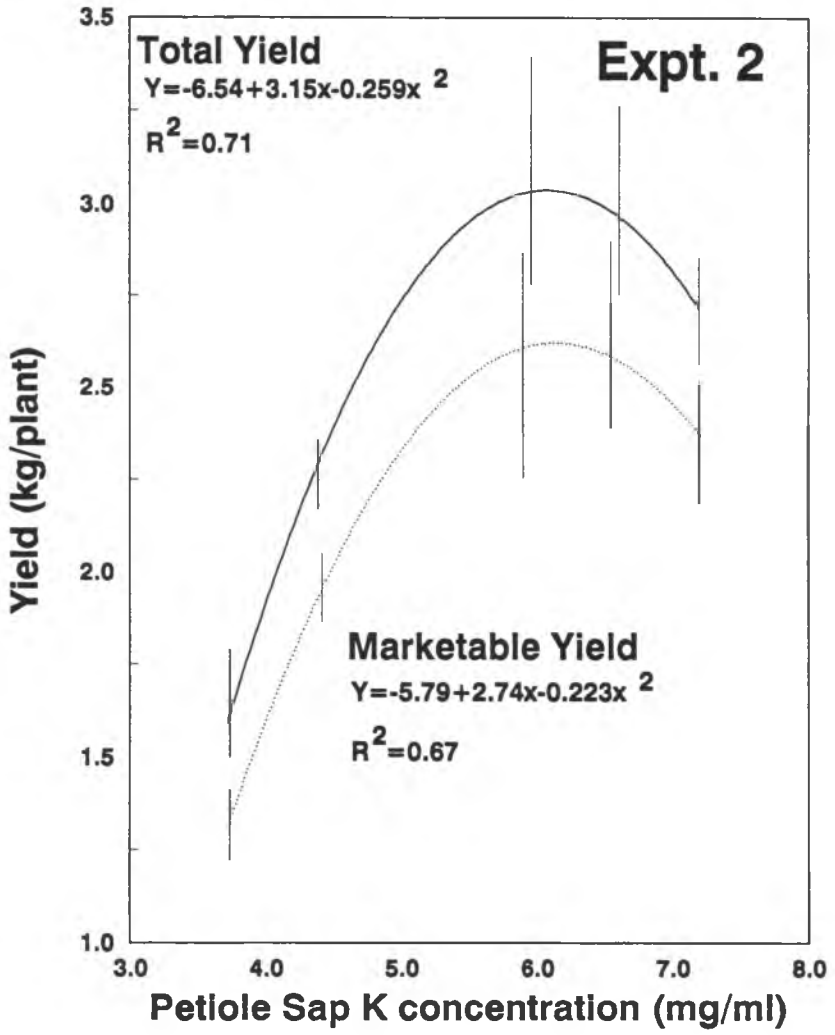

Figure 4.7. Correlation between total and marketable yield (g/plant) and petiole sap K (ug/ml) concentration in Expt 2. Vertical bars represent the standard error of the mean.

Table 4.1. Summary of averaged plant height, number ofanthesis) and stem caliper at 50% anthesis (50 days after planting) in Expt. 1.

K concn. in irrigation (mg/liter)	Plant Height (cm)	Number of Flower Clusters
25	85.8±4.7[z]	3.0±1.1
50	90.0±6.7	3.9±0.7
100	88.9±4.6	4.0±1.3
200	91.6±4.4	4.1±1.5
300	91.2±5.7	4.1±0.8
Sign.		
Linear	*[y]	NS
Quadratic	NS	NS

K concn. in irrigation (mg/liter)	Number of Flowers	Stem Caliper (cm)
25	9.1±3.8	.
50	13.1±3.5	.
100	11.9±3.7	.
200	11.9±3.3	.
300	12.8±2.9	.
Sign.		
Linear	NS	-
Quadratic	NS	-

[z] +/-95% confidence interval.
[y] NS, *, ** Nonsignificant or significant at 5% (*) or 1%(**) levels

Table 4.2. Summary of averaged plant height, number of flower clusters, number of flowers (at or beyond anthesis) and stem caliper at 50% anthesis (54 days after planting) in Expt. 2.

K concn. in irrigation (mg/liter)	Plant Height (cm)	Number of Flower Clusters
25	88.2±7.0	2.6±0.5
50	92.7±6.0	2.7±0.7
100	87.9±5.1	2.9±0.6
200	93.3±5.0	2.8±0.6
300	95.8±5.5	3.0±0.7
Sign.		
Linear	**[y]	NS
Quadratic	NS	NS

K concn. in irrigation (mg/liter)	Number of Flowers	Stem Caliper (cm)
25	7.6±2.0	5.3±0.5
50	8.4±2.9	5.8±0.7
100	9.4±2.8	6.0±0.4
200	9.1±2.9	6.2±0.6
300	9.5±2.4	6.3±0.6
Sign.		
Linear	*	**
Quadratic	NS	NS

[z] +/-95% confidence interval.
[y] NS, *, ** Nonsignificant or significant at 5% (*) or 1%(**) levels

beyond anthesis increased with increasing external feed K concentration in Expt. 2, but not in Expt 1. The data do not strongly support the role of K fertilization in influencing flowering.

The percentage of non-marketable fruit (by number) at the 200 mg K/liter external feed concentration was significantly lower than the other treatments in Expt. 1 (Table 4.3). In Expt. 2 there was no significant difference of non-marketable fruit yields by weight (Table 4.4). Breakdown of non-marketable fruit into individual "cull" categories showed no significant relationships between external K concentrations and specific defects in Expt. 1 (Table 4.3). In Expt. 2., linear regressions of percent non-marketable yields due to small size, blossom end rot and cracking were significant at P= 5% (Table 4.4). There was a negative impact of increasing external K feed concentration on blossom end rot and a positive impact on cracking. Greater blossom end rot at lower K feed concentrations was unexpected, because this defect is known to be caused by calcium defeciency, and calcium levels in the external feed solutions were actually greatest, not least, at the lowest K levels (Table 3.1).

Cracking of tomato fruit can be a function of increased fruit size (Gill and Nandpuri, 1970). The

Table 4.3. Percentages of individual "cull" categories and total non-marketable yields (by number) at each external feed concentration (Expt. 1).

K concn. in irrig. (mg/liter)	Small Size	Blossom End Rot	Miss-hapen	Scars	Cracking
25	3.6	0.3	0.1	0.2	0.05
50	3.8	0.4	0.05	0.05	0.1
100	6.5	0.9	0.05	0.1	0.0
200	2.9	0.05	0.1	0.1	0.05
300	4.5	0.7	0.1	0.05	0.1
Sign.					
Linear	NS[y]	NS	NS	NS	NS
Quadratic	NS	NS	NS	NS	NS

K concn. in irrig. (mg/liter)	Splits	Unusual Scarring	Cat Face	Total
25	0.4	0.05	0.05	25.9±4.4[z]
50	0.2	0.1	0.1	25.9±4.9
100	0.1	0.2	0.05	34.8±6.4
200	0.1	0.05	0.1	15.4±1.8
300	0.2	0.18	0.1	27.6±3.1
Sign.				
Linear	NS	NS	NS	NS
Quadratic	NS	NS	NS	NS

[z] +/-95% confidence interval.
[y] NS, *, ** Nonsignificant or significant at 5% (*) or 1%(**) levels.

Table 4.4. Percentages of individual "cull" categories and total non-marketable yields (by number) at each external feed concentration (Expt. 2).

K concn. in irrig. (mg/liter)	Small Size	Blossom End Rot	Mis-shapen	Scars	Cracking
25	1.6	1.7	0.1	0.0	0.1
50	0.6	1.2	0.0	0.0	0.3
100	1.5	1.8	0.0	0.1	0.5
200	0.5	1.0	0.0	0.0	1.1
300	0.6	1.0	0.0	0.0	0.7
Sign.					
Linear	*[y]	*	NS	NS	*
Quadratic	NS	NS	NS	NS	NS

K concn. in irrig. (mg/liter)	Splits	Unusual Scarring	Cat Face	Total
25	0.0	0.0	0.5	29.8±5.1[z]
50	0.0	0.0	0.1	17.1±2.7
100	0.0	0.0	0.1	21.2±2.3
200	0.0	0.0	0.0	14.8±3.5
300	0.0	0.0	0.1	16.6±4.3
Sign				
Linear	--	--	NS	NS
Quadratic	--	--	NS	NS

[z] +/-95% confidence interval.
[y] NS, *, ** Nonsignificant or significant at 5% (*) or 1%(**) levels.

correlation value (r) for the relationship between average fruit size vs percent (by number) fruit cracking is r=0.81.

Chapter 5

Conclusion

The paper strip test for K appears to be suitable for use with greenhouse tomatoes. Sampling variation from plant to plant and over the crop cycle was low throughout the crop's cycle. However as with NO_3-N, there was considerable day-to-day sampling variation of the petiole sap K concentrations. As with petiole sap NO_3-N, petiole sap K levels can probably be quantified adequately using a running average of weekly data. Potassium in petiole sap responded quadratically to increasing external feed K concentration. Yields responded quadratically to increased K in the external feed solution. The decrease in yield at external K feed solutions above 200 mg K/liter was attributed to high concentrations of K in the feed and not to increased chloride content. I hope to confirm this interpretation with tissue analysis. The optimum external feed concentration for greenhouse grown 'Celebrity' tomatoes appears to be about 200 mg K/liter. The optimum sap concentration for maximum marketable yield appears to be between 5.7 to 6.2 mg K/ml sap.

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